UNCLASSIFIED

a/2177

[redacted]

UNCLASSIFIED

WT-34

UNCLASSIFIED

Classification (Cancelled) (Changed to
By Authority of Mong. Ch. Security Div. 7-16-57
By T. Camp Date 31 JUL 1957

OPERATION GREENHOUSE

SCIENTIFIC DIRECTOR'S REPORT

ANNEX 8.0

GENERAL REPORT OF BLAST STUDIES ON AIRCRAFT

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

NUCLEAR EXPLOSIONS

1951

Statement A
Approved for public release;
Distribution unlimited

DTIC QUALITY INSPECTED 4

[redacted]

UNCLASSIFIED

C 1136

19960212 140

[redacted]

Defense Nuclear Agency
6801 Telegraph Road
Alexandria, Virginia 22310-3398

SSTL 12 July 1995

MEMORANDUM FOR DEFENSE TECHNICAL INFORMATION CENTER

ATTN: OCD/Mr. Bill Bush

Subject: Withdrawal of AD-A995303 from DTIC System.

The Defense Nuclear Agency Security Office requests the withdrawal of the subject report (AD-A995303, WT-34-EX) from the DTIC system.

The original report (WT-34-EX) has been **declassified** and approved for public release. Therefore, the extracted version, (AD-A995303) is obsolete.

This office has enclosed a copy of the original report for inclusion into the DTIC system.

Please notify us of the DTIC accession number, once it is assigned.

FOR THE DIRECTOR:

Josephine B. Wood

JOSEPHINE B. WOOD
Chief, Technical Support

Enclosure:
As Stated

[redacted]

GENERAL REPORT OF BLAST STUDIES ON AIRCRAFT

by

JOSEPH KELLEY, JR.

and

LAWRENCE LEVY

Approved by: ROBERT E. JARMON
Colonel, USAF
Director, Program 8

Approved by: ALVIN C. GRAVES
Scientific Director

Aircraft Laboratory
Wright-Patterson Air Force Base
Dayton, Ohio

Department of Aeronautical Engineering
Massachusetts Institute of Technology
Cambridge, Massachusetts

September 1951

MIT
Dec 76

[redacted]

 [redacted]

Preface

The purpose of this report is to outline the theoretical research that was performed as a basis for Air Force participation in the air and on the ground during Operation Greenhouse. The basic philosophy and reasoning underlying the entire program on the effects of blast on aircraft structures is discussed. There has been no correlation made in this report between the theory developed and experimental data obtained during the tests. This will follow in formal USAF–MIT reports now in preparation.

[redacted]

[redacted]

CONTENTS

	Page
PREFACE	v
ACKNOWLEDGMENTS	vii
CHAPTER 1 INTRODUCTION	1
1.1 Objective	1
1.2 Historical Background	2
CHAPTER 2 CHARACTERISTICS OF THE BLAST	5
2.1 General	5
2.2 Aerodynamic Characteristics	5
2.3 Presentation of Results	6
2.4 Thermal Radiation	6
CHAPTER 3 STRUCTURES AND AEROELASTIC EFFECTS	9
3.1 General	9
3.2 Pressure Loads	10
3.3 Aerodynamic Loads	11
3.4 Elastic Properties of Test Aircraft	12
3.5 Dynamic-analysis Methods	12
3.6 Controlled Motions of Aircraft	13
CHAPTER 4 AIRCRAFT EXPERIMENTAL PROGRAM AT GREENHOUSE	15
CHAPTER 5 RECOMMENDATIONS	17

ILLUSTRATIONS

	Page
CHAPTER 2 CHARACTERISTICS OF THE BLAST	
2.1 Peak Overpressure vs Slant Range for a 50-kt Bomb at Sea Level	19
2.2 Peak Material Velocity vs Slant Range for a 50-kt Bomb at Sea Level	19
2.3 Peak Air Density vs Slant Range for a 50-kt Bomb at Sea Level	19
2.4 Isobars of Peak Overpressure for a 50-kt Bomb at Sea Level	20
2.5 Positions of Shock Front in Space at Various Times after Detonation of a 50-kt Bomb at Sea Level	20
2.6 Ground Intercept of Shock Front vs Time after Detonation of a 50-kt Bomb at Sea Level	20
2.7 Duration at Sea Level of the Positive Pressure Phase of the Blast Wave for a 50-kt Bomb at Sea Level	21

[redacted]

[redacted]

ILLUSTRATIONS (Continued)

Page

2.8 Comparison of Air Density in the NACA Standard and the Eniwetok Standard Atmospheres 21

2.9 Comparison of Air Temperature in the NACA Standard and the Eniwetok Standard Atmospheres 21

CHAPTER 3 STRUCTURES AND AEROELASTIC EFFECTS

3.1 The Wagner Function 22

[redacted]

[redacted]

UNCLASSIFIED

This document consists of 32 plus 4 pages
(counting preliminary pages)
No. 4 of 150 copies, Series A

Scientific Director's Report of Atomic Weapon Tests at Eniwetok, 1951

Annex 8.0

General Report of Blast Studies on Aircraft

[redacted]

[redacted] UNCLASSIFIED

[redacted]

[redacted]

Distribution

	Copy
DEPARTMENT OF DEFENSE	
Armed Forces Special Weapons Project (Sandia)	1 – 3
Armed Forces Special Weapons Project (Washington)	4 – 15
ARMY	
Army Field Forces	16
Assistant Chief of Staff, G-3	17
Assistant Chief of Staff, G-4	18 – 19
Chief of Ordnance	20 – 24
Operations Research Office (Johns Hopkins University)	25 – 26
Quartermaster General	27 – 31
NAVY	
Bureau of Aeronautics	32 – 35
Bureau of Ordnance	36 – 37
Chief of Naval Operations	38 – 39
Chief of Naval Research	40
Commandant, Marine Corps	41
AIR FORCE	
Air Force Cambridge Research Center	42
Air Research and Development Command	43 – 46
Air Targets Division, Directorate of Intelligence (Phys. Vul. Branch)	47 – 48
Assistant for Atomic Energy	49 – 50
Assistant for Development Programming	51
Assistant for Materiel Program Control	[redacted]
Deputy Chief of Staff for Development (AFDRD)	53
Director of Operations (Operations Analysis Division)	54
Director of Plans (AFOPD-P1)	55
Director of Requirements	56 – 57
Director of Research and Development	58 – 59
Eglin Air Force Base, Air Proving Ground	60 – 61
Ent Air Force Base, Air Defense Command	62 – 63
Kirtland Air Force Base, Special Weapons Command	64 – 66
Langley Air Force Base, Tactical Air Command	67 – 68
Maxwell Air Force Base, Air University	69 – 70
Offutt Air Force Base, Strategic Air Command	71 – 73
1009th Special Weapons Squadron	74
Rand Corporation	75 – 76
Scott Air Force Base, Air Training Command	77 – 78
Wright Air Development Center	79 – 81
Wright Air Materiel Command	82 – 83
ATOMIC ENERGY COMMISSION	
Atomic Energy Commission, Washington	84 – 86
Los Alamos Scientific Laboratory, Report Library	87 – 91
[redacted] Corporation	92 – 93
Technical [redacted]n Service, [redacted]s)	94 – 149
[redacted]s Group, TIS	150

[redacted]

[redacted]

Acknowledgments

During the 18 months preceding Operation Greenhouse, the staff of the Massachusetts Institute of Technology Aero-Elastic and Structures Research Group, under the direction of Raymond L. Bisplinghoff and H. G. Stever, was involved in a detailed program of research on the effects of blast loading on aircraft structures. All the personnel performing this research have contributed much to the entire program and to the preparation of this report. In particular, James W. Mar, Norman P. Hobbs, and S. Dean Lewis have materially aided in the preparation.

There also are many organizations throughout the country without whose splendid cooperation it would have been impossible to accomplish the objectives of the program in the allotted time. Specifically, acknowledgments are due to the personnel of the Los Alamos Scientific Laboratory; the Structures Branch of the Aircraft Laboratory, Wright Field; the Ballistic Research Laboratories and the Development and Proof Services, Aberdeen Proving Ground; Headquarters, Special Weapons Command, Kirtland Air Force Base; the Boeing Aircraft Co., Seattle, Washington; and the Lockheed Aircraft Corp., Los Angeles.

[redacted]

[redacted]

Chapter 1

Introduction

1.1 OBJECTIVE

In considering problems associated with strategic bombing using atomic weapons, two significant and as yet unanswered questions that are vitally important to the airplane structural designer have confronted Air Force tactical planners. The first of these two questions is one of current importance. It inquires as to the position relative to an atomic explosion that can be occupied by present-day military aircraft without incurring structural damage. The second involves future air weapons. It is concerned with the determination of criteria for designing structures of future air carriers which are designated for the accomplishment of tactical and strategic missions using atomic weapons.

For many years military aircraft have been designed by criteria promulgated by the Air Force according to the mission the aircraft is intended to perform. In many cases it has taken years of operating experience to formulate these criteria, and, when aircraft are applied to new tactical missions, it is generally necessary to reexamine design requirements and to supplement them so as to provide sufficient structural soundness. This is not always an easy task. In some cases sound design criteria for a particular type of aircraft are not formulated until some operating experience has been obtained. In other cases design criteria can be based on theoretical studies and laboratory experiments and can be incorporated into new designs at their inception.

The formulation of structural design criteria for aircraft employing atomic weapons is necessary if the operational mission of such aircraft is to be carried out successfully. Unfortunately the problem is an involved one because of the severe difficulties associated with obtaining experimental data. Up to the time of Operation Greenhouse, 13 U. S. atomic bombs had been detonated, and yet there had been no systematic compilation of data pertaining to the effects of blast loads on aircraft structures due to severe instrumentation requirements. This prevented the formulation of rational design criteria which could be based on a correlation of theory with experimental data.

In November 1949, the United States Air Force placed a contract (AF33(038)-8906) with the Massachusetts Institute of Technology (MIT), the purpose of which was to study the effect of blast on aircraft in flight. It became apparent that a well-organized experimental program would be needed in order to help answer the two questions pointed out earlier. In particular, the first of these questions was the one that had to be attacked from both experimental and theoretical points of view before the actual structural design criteria could be formulated. An accelerated study of the entire program was conducted with the objective of specifying completely and clearly the characteristics of the external loading and of the aircraft itself which would need to be measured in full-scale flight and ground research. These preliminary studies were given high priority so that pertinent decisions could be made at the earliest possible date regarding the entities to be measured.

It was decided to use instrumented drone and manned aircraft that would operate in the blast field and record aerodynamic and structural data of interest. The drone aircraft were to be B-17's and T-33's, and the manned aircraft were an XB-47 and two B-50's. Concurrently, a program of theoretical research was initiated

[redacted]

for the purpose of carefully studying the entire problem. The efforts that were expended on this program in carrying out the responsibilities prior to the Greenhouse tests were considerable and were a necessary groundwork in preparation for later formulation of design criteria. They involved the calculation of the complete elastic and inertial properties of the drones and manned aircraft to be used in the tests and the formulation of satisfactory theories to predict the dynamic stresses in their structures under rapidly changing external loads.

The determination of the character of the external load involves two steps. The first step entails a study of the theoretical methods and experimental data for predicting the time history of the free-air overpressure for given-yield atomic bombs at all points in the disturbance field. The sparseness of reliable experimental data from previous tests served to make the problem more difficult. The second step entails a determination of the effect of the traveling pressure wave in producing forces and moments on the airplane structure. This is an extremely complex problem in nonstationary aerodynamics. The solution yields the dynamic stresses at arbitrary points in the airplane structure when subjected to the blast wave. A comparison of the computed dynamic stresses with the allowable stresses of the aircraft determined the positions in space that the aircraft occupied during the Greenhouse tests.

In a flying airplane the air forces and moments on the airplane structure are not only functions of the pressure wave but also functions of the manner in which the airplane structure deforms. Therefore it was deemed desirable to supplement the flight program with a program on the ground whereby the coupling effect of the structure on the air forces and moments could be minimized. Various types of models were designed and constructed for this purpose. The Air Force instrumented these models in such a manner that it would be easy to correlate the measured loads with the results of the basic research being conducted as outlined above.

The drones and manned aircraft were flown in predetermined positions as shown in the Project 8.1 report, and the response of the aircraft structure to the blast disturbance was measured.

The ground-program data in Project 8.2 were obtained, and they supplemented the airborne measurements.

No attempt is made in this report to present a correlation of the measured data obtained with those of the theoretical research conducted at MIT because the reduced data from the air and ground programs became available at approximately the same time that this report was being written. The primary purpose of this report is to show what basic philosophy and reasoning were used to define the experimental programs conducted at Eniwetok and to review generally the theoretical research that was performed in order to locate the aircraft for the various shots.

The detailed correlation of all the above-mentioned data, along with the formulation of the structural design criteria, will be reported in formal USAF–MIT reports which will be forthcoming during 1952. These reports will be divided into six volumes as follows: Volume I, Summary Report; Volume II, Characteristics of the Explosion; Volume III, Structural and Aero-Elastic Effects; Volume IV, Correlation of Measured Loads with Theory; Volume V, Structural Design Criteria; Volume VI, Tactical Procedures.

1.2 HISTORICAL BACKGROUND

The general blast problem from the offensive and defensive points of view, as applied to the destruction of buildings in the former case and to structural air-raid precautions in the latter case, has been extensively studied both theoretically and experimentally. A necessary adjunct to this work has dealt with the behavior of shock waves in air and in particular with the shock waves produced by explosions. Studies of the manner in which the shock waves cause damage and of the interaction of shock waves with obstacles have also been made. Division 2 of the National Defense Research Committee has issued several reports on these topics, and an excellent detailed bibliography can be found in the Summary Technical Report of Division 2, Volume I.

The effects of blast on aircraft have been investigated primarily from the offensive stand-

[redacted]

point, i.e., crippling of an airplane so that it cannot perform its mission. These investigations are being made to determine what combination of the blast parameters will yield an optimum weapon. Extensive tests in this field are being conducted at the Terminal Ballistics Laboratory at the Aberdeen Proving Ground. Briefly, bare TNT or Pentolite charges of different weights have been exploded at various distances from aircraft such as the B-17, SB2C-1, A-26, and P-47.

All the blast work described in the preceding paragraphs has served as a valuable background for Greenhouse Program 8. It should be noted that there is an important difference in philosophy between Greenhouse Program 8 and the above-mentioned work. The Aberdeen program has been concerned primarily with the offensive destruction of aircraft, whereas the Greenhouse tests have been designed to obtain general structural damage information that would be of benefit both offensively and defensively.

One of the first cases wherein the prevention of blast damage to aircraft became important was in connection with the safe launching of airborne rockets. The blast of the rocket in some instances caused local failures of the parent aircraft, and investigations were made to determine the cause of the damage. The Germans also did some work on the effect of detonating bombs in the vicinity of flying aircraft and conducted tests in which airplanes were flown through the blast waves emanating from 50-kg charges. Acceleration measurements at several locations in the airplane were made. Since the airplane used in these tests was manned, the overpressures were of necessity quite low.

Aircraft have participated in most of the atomic explosions conducted by the United States. Usually the airplanes were not participating as specimens in the blast field but were acting as instruments to determine the character of the nuclear phenomena. There were, however, complete airplanes and components of airplanes disposed on the ships which comprised the primary target array of the Bikini Able Test. Their main purpose was to obtain qualitative structural data. The Bureau of Aeronautics Group of the United States Navy was responsible for the complete airplanes, and the Army Air Forces assumed the responsibility for the components of airplanes. In all, there were 73 complete airplanes exposed to the Bikini Able Shot.

In addition, there were drone aircraft flying in the vicinity of the explosions. The prime objective in the use of these airplanes was to gather nuclear samples from the cloud; hence the obtaining of structural information was secondary. Nevertheless, significant information concerning the effect of the blast was obtained from inspection of a B-17 drone which was directly over the burst point of the Bikini Baker Test. There is some question as to the amount of blast energy which appeared above the water. However, the most reliable estimates indicate that the lowest of the airplanes was subjected to more than 1 psi of overpressure. The lowest B-17 apparently suffered some damage to its bomb-bay doors, but this damage was insufficient to prevent the airplane from accomplishing its mission and returning safely to its home base.

In Operation Sandstone the Air Materiel Command of the USAF instrumented several B-17 drones for the measurement of the shock-wave effects; however, the same drones were used to obtain air samples, and the structural measurements were a secondary mission. The instrumentation consisted of wire strain gauges to measure strain in the wing structure, pressure gauges, accelerometers, and oscillographs for recording the data. Complementing this equipment, cameras were used to obtain a record of the instrument panel. Unfortunately instrumentation difficulties did not permit adequate correlation and examination of the data.

There has been some theoretical work on the problem of determining safe overpressures for flying airplanes. Owing to a lack of information on the problem, the theoretical work has tended to be overly conservative. The purpose of Program 8 was to correct this situation.

[redacted]

Chapter 2

Characteristics of the Blast

2.1 GENERAL

The characteristics of the blast are conveniently divided into two groups, the aerodynamic and the thermal-radiation characteristics. The aerodynamic characteristics of the blast determine the overpressure and material velocity at any point around the explosion. This information is required in order to calculate the blast loads on an arbitrarily located airplane. Knowledge of the character of the thermal radiation is required for the determination of the heating of aircraft in flight.

The characteristics of the blast were based on previous work, both theoretical and experimental. A peak overpressure vs distance curve for points at sea level was taken from a Los Alamos report. The Fuchs altitude correction was used to obtain the overpressure at points above sea level. The normal shock relations then permitted the calculation of the peak material velocity, the peak density, and the shock velocity at any point. Integration of the inverse shock velocity gave the time of arrival of the shock wave. The scaling law was used for determining results for different yields. The time history of the overpressure and the material velocity at a fixed point were assumed in the exponential form. Theoretical results were used for the characteristics of the thermal radiation.

2.2 AERODYNAMIC CHARACTERISTICS

Experimental data from several sources were collected, including both TNT and nuclear explosion data. After a survey of these data the decision was made to use the data supplied to the Los Alamos Scientific Laboratory by C. W. Lampson.[1] These data, which were based on previous nuclear explosions, were presented for a nuclear-energy release equivalent to 50 kt of TNT, normally referred to as a "50-kt bomb," exploded on a tower.

The data originally received were plotted on a chart of Eniwetok Atoll with ten concentric circles. In order to extend and smooth the data as scaled from the chart, the equations of Hirschfelder, Littler, and Sheard[2] were fitted to the data. The plotted sea-level curve is shown in Fig. 2.1.

An air shock traversing a medium is influenced by any changes in the medium. In order to calculate the effects of a very large bomb detonated at one altitude at points at a greatly different altitude, a correction is necessary. The Fuchs altitude correction[3] was applied to find the peak overpressure at points in the blast field. The "standard Eniwetok atmosphere" discussed in the next paragraph was used in applying the Fuchs corrections.

The atmospheric conditions which were determined before and after each of the Sandstone tests[4] were the basis for a standard Eniwetok atmosphere. The data were fairly uniform, considering the relatively long time interval covered in obtaining the data. Comparison with the National Advisory Committee for Aeronautics (NACA) standard atmosphere indicated that the latter would not be a good approximation.

In order to be easily usable in the Fuchs altitude correction, the variations of temperature and density must be functions of the form used in defining the NACA standard atmosphere. New constants were determined to give a good fit to the Sandstone data. The variations of density and temperature in the standard Eniwetok atmosphere, determined in this manner, are shown in Figs. 2.8 and 2.9.

When the atmospheric conditions ahead of the shock wave and the overpressure in the shock are known, then the peak material velocity, the peak density, and the velocity of the shock front may be computed through the use of the Rankine-Hugoniot normal shock relations.

The basic 50-kt peak overpressure curve for sea level, Fig. 2.1, was modified for the various bomb yields by means of the pressure-scaling law.

The exponential approximation form for the variation of overpressure with time at a fixed point was used:

$$\Delta p = \Delta p_s \exp\left(-a\frac{t}{t_0}\right)\left(1-\frac{t}{t_0}\right) \qquad (2.1)$$

where Δp is the overpressure at a fixed distance
Δp_s is the peak (positive) overpressure
t is the time after shock arrival
t_0 is the duration of the positive pressure phase
a is a constant (at the fixed distance).

The positive duration of the pressure phase was taken from theoretical results. The value of a is determined by the ratio of the peak positive to peak negative overpressures which was obtained from theoretical results.[5]

A similar equation was assumed to apply for the time variation of the material velocity at a fixed point:

$$w = w_s \exp\left(-a'\frac{t}{t_0'}\right)\left(1-\frac{t}{t_0'}\right) \qquad (2.2)$$

where w is the material velocity at a fixed distance
w_s is the peak (positive) material velocity
t is the time after shock arrival
t_0' is the duration of the positive material velocity phase
a' is a constant (at a fixed distance).

2.3 PRESENTATION OF RESULTS

Figures 2.1 through 2.9 are illustrations of the work done in preparation for Operation Greenhouse. In cases where yield and burst altitude influence the results presented in the figures, Easy Shot data are used. Easy Shot was planned as a nuclear-energy yield equivalent to 50 kt of TNT, with detonation on a tower.

Figure 2.2 shows the variation of peak material velocity with slant range. These curves are based on Fig. 2.1 and the initial conditions at each point in space, and they were calculated by the use of the normal shock relations. The initial conditions were based on the standard Eniwetok atmosphere.

Figure 2.3 shows the variation of peak air density with slant range. These curves were computed by the method used in Fig. 2.2.

Figure 2.4 shows isobars of the blast field; they are lines of constant peak overpressure. This figure presents the data of Fig. 2.1 in a form which was more useful for certain applications, such as locating aircraft in flight at certain overpressures throughout the blast field.

Figure 2.5 shows the shape and position of the shock front at various times. This information was necessary in positioning aircraft for the test since the aircraft traveled an appreciable distance between detonation time and shock-arrival time.

The velocity of the shock wave at any point in space was derived from the shock strength and initial conditions at that point by the use of the normal shock relations. The time of arrival of the shock wave at any point in space was calculated by integrating the reciprocal of the shock velocity along the path from the detonation point to the desired point in space. Figure 2.5 was derived by this process.

Figure 2.6 shows the position of the shock wave at sea level plotted against time after detonation. These data were derived by the process used in obtaining Fig. 2.5 except that all the points were taken at sea level. This type of curve was useful in finding the time of arrival of the shock front at various ground stations.

Figure 2.7 shows the variation of the positive-pressure-phase duration with range for sea-level conditions.[6]

2.4 THERMAL RADIATION

The time history of the thermal-radiation intensity has been calculated.[7] For the present

purpose the variation of total energy with distance is sufficient. This is given by

$$Q = \frac{105.8\ (kt)\ e^{-kD}}{D^2}$$

where Q is the thermal energy in the plane perpendicular to the line of sight to the burst point (British thermal units per square foot)
kt is the energy yield of the explosion
D is the distance from the explosion
k is the atmospheric thermal-radiation attenuation coefficient.

In the estimation of the effect of thermal radiation on nonmetallic materials, the concept of critical energy[8] applies. Useful values are
9 7 Btu/sq ft for slight burns on human skin, 30 Btu/sq ft for flaming of rubber, and 18.5 Btu/sq ft for destruction of the doped surface of doped aircraft fabric without burning of the fabric. The critical energies are given for normal irradiation; therefore Q must be reduced by cos i for comparison with the critical energies. Here i is the angle of obliquity of the radiation striking the material.

The nature of the effect of the thermal radiation on the metallic structure of an aircraft is different. Paint on the surfaces may be scorched; however, this is not critical for test work. The metal will be heated, and it may melt or decrease in strength, endangering the soundness of the structure.

For the relatively thin skin of aircraft the temperature increase can be considered to be uniform throughout its thickness.[9] The temperature increase of the aluminum skin can then be calculated as

$$\Delta T = \frac{\alpha \cos i\ Q}{\rho c t}$$

where T is the temperature increase (degrees Fahrenheit)
α is the absorptivity of aircraft surface
i is the angle of obliquity of the radiation on the skin
ρ is the density of aluminum
c is the specific heat of aluminum
t is the thickness of the plate.

The temperature increase of the smaller-gauge portions of the skin of the airplane wing and horizontal tail was calculated. A temperature rise of 300°F, corresponding to approximately a 15 per cent decrease of yield stress, was considered allowable.

REFERENCES

1. C. W. Lampson, Pressure-Distance Curves, Document No. LAB 57C, Dec. 9, 1949 (Secret, Restricted Data).
2. J. O. Hirschfelder, D. J. Littler, and H. Sheard, "Hydrodynamics of the Blast," Los Alamos Technical Series, Report LA-1021, Vol. VII, Part II, Chap. 7, p 30, 1947.
3. J. O. Hirschfelder, D. J. Littler, and H. Sheard, "Hydrodynamics of the Blast," Los Alamos Technical Series, Report LA-1021, Vol. VII, Part II, Chap. 9, p 17, 1947.
4. Sandstone Report No. 35.
5. J. O. Hirschfelder, D. J. Littler, and H. Sheard, "Hydrodynamics of the Blast," Los Alamos Technical Series, Report LA-1021, Vol. VII, Part II, Chap. 7, p 11ff, 1947.
6. Sandstone Report No. 20.
7. "The Effects of Atomic Weapons," p 180, U. S. Government Printing Office, Washington, 1950.
8. "The Effects of Atomic Weapons," p 199, U. S. Government Printing Office, Washington, 1950.
9. C. D. Coulbert et al., Temperature Response of Infinite Flat Plates and Slabs to Heat Inputs of Short Duration at One Surface, Department of Engineering, University of California at Los Angeles, 1951.

[redacted]

Chapter 3

Structures and Aeroelastic Effects

3.1 GENERAL

The damage incurred by an airplane immersed in the blast field of an atomic bomb is separated into two categories: (1) The high overpressure associated with the shock wave and the reflection of this high overpressure in the shock front can cause local damage, such as the buckling of fuselage ribs, the crumpling of control surfaces, the crushing of doors, etc.; and (2) the high material velocities (or gust velocities) immediately behind the shock wave can cause the angle of attack of the wing to change appreciably and suddenly, thus subjecting the airplane to an increase in load factor. Since the shock wave is traveling at approximately the speed of sound, the imposition of both the overpressure and the gust velocity occurs almost instantaneously, and the results of both effects must be treated as problems in the transient stress analysis. The importance of the superposition of the gust damage and overpressure damage is not clearly defined as yet, but it is felt that, for most parts of the airplane structure, the two effects can be considered independently.

Theoretical treatment of the overpressure damage even on a very simplified basis is extremely difficult. In order to meet the deadline for the Greenhouse tests, recourse was made to subjecting portions of representative airplanes to blasts from small TNT and Pentolite charges. It should be remembered that the duration of the positive phase of the pressure wave from an atomic explosion is of the order of 1 sec, whereas in a similar overpressure range the positive phase of the pressure wave from a 500-lb charge of TNT is in the neighborhood of 40 msec. Overpressure reflection effects are primarily the result of an impulse transmitted to the local airplane structure, and the origin of the impulse is the interaction of the shock front with the structure. Hence the magnitude of this impulse is very insensitive to the duration of the positive phase beyond a certain threshold duration. The high overpressure cannot induce large bending moments in the main structural members, for example, a wing, since these high overpressures equalize very rapidly on both sides, and the net effect is small. Thus most of the important aspects of the overpressure damage can be duplicated by the exposure of aircraft components to the blast from small charges. One very important factor which has been missing from these tests with small TNT and Pentolite charges is the forward velocity of the airplane. It is felt that the exclusion of this factor tends to make the experimental results conservative.

All airplane-design criteria include a criterion for gusts. This gust criterion is based on a steady-state sharp-edged gust formula and includes an alleviation factor which takes into account the vertical motion caused by the gust. Thus the gust criterion represents a static approach which assumes the airplane to be a rigid body. There are a number of reasons why the usual approach cannot be used in the investigation at hand. The effective design gust velocity as specified in design criteria is in the neighborhood of 30 ft/sec, whereas at an overpressure of 1.5 psi the peak gust velocity is approximately 78 ft/sec at sea level. Owing to the rapidity with which the entire airplane is immersed by the high gust velocity, the airplane can no longer be considered as a rigid structure. The behavior of elastic airplanes under the influence of gusts has been extensively studied, and methods of analysis have been developed. Newer and better methods are

[redacted]

being formulated, and much work remains before the complete problem will become more tractable.

The gust-damage problem may be broken down into three parts: (1) the determination of the aerodynamic loads which result from the material velocity behind the shock and from the motion of the aircraft; (2) the determination of mode shapes and frequencies; and (3) the solution of the airplane equations of motion using the aerodynamic loads to determine dynamic loads and stresses acting on the aircraft. The basic assumptions and methods employed in these three problems are outlined in the following pages. The detailed analysis will appear in forthcoming USAF–MIT reports.

In addition, the stability of aircraft encountering violent gusts must be considered. This problem is also briefly described in the following pages.

3.2 PRESSURE LOADS

The determination of the pressure loads on an aircraft structure due to a blast wave is complicated by two principal factors: (1) the incomplete state of the theory of shock phenomena and (2) the existence of a gust load which is concurrent with the pressure load. The first factor makes it necessary to use experimental techniques to complement and corroborate the analytical approach. The second factor makes it highly desirable to organize these experiments in such fashion that the pressure and gust effects can be separated.

On the basis of the foregoing considerations an experimental program was organized for the investigation of the critical value of blast overpressure which would result in structural damage to an aircraft sufficient to cripple it. This program consisted principally in subjecting full-scale planes or elements thereof to blasts caused by the explosion of Pentolite and TNT charges.

It was decided that the blast test program should be conducted at Aberdeen Proving Ground, Aberdeen, Maryland, because of the unusual facilities available for the type of test contemplated and the presence of personnel with considerable experience in fields related to that under study.

Based on the results of the Bikini tests, those portions of an aircraft which are generally most vulnerable to blast effect, and at the same time critical in the operation of the plane, are the control surfaces (particularly the tail surfaces). For this reason the principal attention of the experimental portion of the blast-damage program was directed to the tail surfaces of the aircraft.

Since the extent and type of damage which is suffered by an aircraft is strongly affected by the type of construction of the critical elements, two types of aircraft were used in the test, namely, the F-86 fighter and the B-17 bomber. The F-86, since it is a high-speed fighter, has metal-covered control surfaces with relatively heavy-gauge skin. In contrast, the B-17 has fabric-covered tail control surfaces. A T-33 was actually desired for these tests, but, since none were available, it was decided to use the F-86, which is similar to the T-33.

The B-17 control surfaces were subjected to computed overpressures ranging from 0.25 to 2.25 psi with the blast directed normal to the surfaces and to computed overpressures ranging from 2.00 to 3.2 psi with the blast directed obliquely against the surface. In the latter group of firings the angle of obliquity was such that a line from the charge to the surface made an angle of 25° with the normal to the surface.

The F-86 control surfaces were subjected to computed overpressures ranging from 1.75 to 8.50 psi with the blast directed normal to the surface.

In these tests three sizes of explosive charges, 2, 50, and 500 lb, were fired at each overpressure. This permitted observation of any effects due to varying duration of the positive phase of the blast wave.

With the size of charges used, the action of the material velocity behind the shock was relatively small since its duration was short, and the effects on the aircraft elements could be ascribed almost entirely to the pressure impulse effect.

As a result of these tests it was decided that for Operation Greenhouse the maximum safe overpressure for the B-17, based on tail surfaces as the critical elements, was 1.5 psi. The maximum safe overpressure for the T-33,

based on the tail surfaces as the critical elements, was 2.0 psi.

3.3 AERODYNAMIC LOADS

The first step in determining the dynamic loads or stresses in an aircraft structure is to define the aerodynamic loads. These loads result, in the case being considered, from the material velocity behind the shock wave. An approximate loading may be found by assuming that the air loads react instantaneously to the gust, that is, that the lift acting on the airplane at any time corresponds to the angle of attack and dynamic pressure at that time. This is the basis for the sharp-edged gust formula which has been used extensively for design:

$$\Delta n = \frac{\rho U w C_{L\alpha A}}{2(W/S)} \qquad (3.1)$$

where Δn is the change in lift on the airplane in g units
- ρ is the ambient air density in slugs per cubic foot
- U is the airplane velocity in feet per second
- w is the gust velocity, assumed vertical, in feet per second
- S is the wing area in square feet
- W is the airplane weight in pounds
- $C_{L\alpha A}$ is the slope of the airplane lift coefficient per radian.

The sharp-edged gust formula is inadequate for the present investigation. Actually, the change in lift on the airplane lags the change in angle of attack. Since the material velocity following a shock wave reaches its peak almost immediately and then decays quite rapidly, the effect of the lag is of great importance. For example, in the limiting case in which the gust attains its peak in zero time and decays to zero in a negligible time, the maximum change in loading, considering the lag, is only about half that given by the sharp-edged gust formula.

An allied inadequacy in the sharp-edged gust formula lies in the fact that lift due to motion of the airplane resulting from the gust is neglected. Obviously, if the airplane reaches its peak load factor immediately, the lift due to motion is unimportant. However, if the time to peak load factor is finite, the fact that the airplane tends to ride with the gust may give rise to considerable alleviation. Thus the aerodynamic load due to motion of the aircraft as well as that due to the gust must be considered.

If an airplane in flight is suddenly subjected to an infinite vertical gust field of velocity w, the ratio of instantaneous change in lift to the steady-state change in lift given by Eq. 3.1, assuming that the airplane is restrained in vertical motion, is known as the "Wagner function" (see Fig. 3.1). In Fig. 3.1, s is a nondimensional time variable given by

$$s = \frac{2Ut}{c} \qquad (3.2)$$

where t is the time in seconds
c is the chord in feet.

$\Phi(s)$ is the Wagner function; $\Delta L(s)$ is the change in lift per foot of span as a function of s; and ΔL_∞ is the steady-state lift per foot of span corresponding to time equal to infinity. A close analytical approximation to the Wagner function is given by

$$\Phi(s) = 1 - 0.165e^{-0.0455s} - 0.335e^{-0.300s} \qquad (3.3)$$

The Wagner function is based on two-dimensional theory. Although some work has been done on unsteady aerodynamics of finite span wings,[1] two-dimensional theory, employing the three-dimensional slope of the lift curve, is apparently adequate.[2]

A physical picture of the Wagner function may be given by considering the direct and induced effects of the trailing vortices parallel to the span of the wing and the circulation of the wing. When the gust strikes the wing, circulation is immediately produced on the wing which, by itself, would give a lift equal to ΔL_∞. However, a system of trailing vortices starts at the trailing edge of the airfoil. These vortices, together with their induced effects, decrease the lift given by the above circulation by one-half at time equal to zero. As this system of vortices drifts downstream, its effect, as well as its induced effects, becomes smaller; therefore the total lift on the airfoil increases. When the trailing vortices are infinitely far downstream, they have no effect, and the lift reaches its steady-state value, ΔL_∞.

[redacted]

In the blast case the airfoil is not instantaneously immersed in a gust field as in the Wagner case. However, since the shock wave passes over the airfoil extremely rapidly, the Wagner function offers a very close approximation to the actual lift; therefore the Wagner function was used to represent the lift produced by a step-function gust behind a shock wave. In the blast case being considered, the material velocity cannot be represented by a step function; therefore the Wagner function must be employed in a superposition integral involving the actual gust-time relation. The exponential form of the gust-velocity variation was used (Eq. 2.2).

The Wagner function includes no apparent mass effects; therefore the apparent mass lift must be added to the above-mentioned lift to determine the total lift.

The lift due to motion may be found by using the velocity at the three-quarter chord in a superposition integral with the Wagner function.[3] Again the apparent mass effects must be included separately.

The largest contribution to moment is produced by the lift on the tail, which may be found in a manner similar to that outlined above. The moment on the wing corresponding to the above-mentioned lift forces may be found as a result of the fact that the apparent mass forces act at the 50 per cent chord, whereas the rest of the lift, except for one term, acts at the one-quarter chord.[4]

3.4 ELASTIC PROPERTIES OF TEST AIRCRAFT

Before a dynamic analysis can be accomplished, the mode shapes and frequencies of the airplane must be found. For the problem at hand it was expedient to consider only wing modes. These may be found including fuselage pitching or by assuming that the fuselage has infinite pitching moment of inertia. This assumption causes very little error in the resulting mode shapes and frequencies and has been used extensively in dynamic analyses. In this section a short description of the method employed to find mode shapes and frequencies, neglecting pitching, is presented.

The first step in the calculation of the mode shapes and frequencies for an airplane wing is the construction of the dynamic model. The dynamic model of the wing represents an approximation to the true inertia and elastic properties of the wing. The greater the number of point masses included in the dynamic model, the more accurate are the mode shapes and frequencies calculated for the actual wing. A dynamic model with an infinite number of point masses would be a true representation of the actual wing and hence would yield exact mode shapes and frequencies. If the dynamic model contains twice as many masses as the number of mode shapes and frequencies required, a fairly good approximation to the actual mode shapes and frequencies will be obtained.

After the distribution of point masses has been determined, the deflection influence coefficients for these points must be found. These influence coefficients represent the deflection at one mass point due to a unit force at another mass point. They may be found by utilizing the bending and torsional stiffnesses of the wing.

Using the influence coefficients, an equation of motion for each point mass may be written. With the assumption of sinusoidal motion, these equations become a set of n simultaneous algebraic equations, where n is the number of mass points. Solution of these equations can yield n sets of mode shapes and frequencies; however, as mentioned previously, only the first n/2 sets can be used. The resulting mode shapes are in the form of coefficients, $A_i^{(r)}$, which represent the normalized displacement of the ith point in the rth mode.

Each of the test airplanes for Greenhouse was subjected to a ground vibration test at Wright Field in order to determine experimentally the natural frequencies of the wing. These frequencies were used as checks on the theoretical analyses.

3.5 DYNAMIC-ANALYSIS METHODS

With the aerodynamic loads and the mode shapes and frequencies of the wing known, a dynamic analysis can be made. The problem can be simplified considerably by neglecting rigid-body pitching and the air forces which result from the modal vibrations. These assumptions remove aerodynamic coupling among the equations of motion. The equations may be decoupled elastically by a transforma-

[redacted]

tion from generalized to normal coordinates. This transformation is represented by the equation

$$h_i(t) = \sum_{r=1}^{p} A_i^{(r)} q_r(t) \tag{3.4}$$

where $h_i(t)$ is the absolute displacement of point i
$A_i^{(r)}$ is the mode shape coefficient for the *i*th point in the *r*th mode
$q_r(t)$ is the *r*th normal coordinate
p is the number of modes being used.

The resulting equations of motion are

$$M_0\ddot{q}_0(t) = Q_0(t)$$
$$M_r\ddot{q}_r(t) + M_r\omega_r^2 q_r(t) = Q_r(t) \qquad r = 1, 2, \ldots, n \tag{3.5}$$

where M_r is the generalized mass corresponding to the *r*th normal coordinate and is given by

$$M_r = \sum_{i=0}^{n} m_i \left[A_i^{(r)}\right]^2 \tag{3.6}$$

where m_i is the mass at point i
n is the number of mass points
ω_r is the natural frequency of the *r*th mode
$Q_r(t)$ is the generalized force corresponding to the *r*th normal coordinate and is given by Eq. 3.7.

$$Q_r(t) = \frac{\delta W_r}{\delta q_r} \tag{3.7}$$

where δW_r is the work done by all forces other than inertia or conservative forces in a virtual displacement δq_r of the *r*th normal coordinate. The subscript 0 refers to the rigid-body vertical translation mode.

With the equations of motion expressed in terms of normal coordinates, the remainder of the task lies in the solution of these equations of motion. Since they are uncoupled, they may be solved separately by the method of undetermined coefficients, yielding the $q_r(t)$. The loads or stresses on the aircraft may then be found from the deflections.

The methods outlined above were used in conjunction with the Aberdeen results to determine the proper positions for the test airplanes.

3.6 CONTROLLED MOTIONS OF AIRCRAFT

Work was done on the determination of the resulting motion of an aircraft enveloped by a blast. This motion was obtained using conventional dynamic-stability theory into which the blast characteristics were placed as a forcing function.

For the longitudinal case, a blast approaching from directly below will cause the airplane first to gain altitude and then to lose altitude. This is due to the change-over from the positive phase to the negative phase of the blast. Because of the inertia characteristics of the airplane, the time of change in direction of the response of the airplane does not correspond to the end of the positive phase of the blast. Concerning the angle of pitch, the airplane will initially pitch downward and then later pitch upward. The greater the static margin of the airplane, the greater will be the angle of pitch. The pitching generally tends to decrease the total altitude gained during the initial upward push.

If an autopilot is installed in the airplane, the pitching of the airplane will tend to be suppressed. Also, the responses of the airplane will be more oscillatory in nature.

The effect of elasticity on the motion of the airplane is usually small, and for most cases the assumption of a rigid airplane is good. For large, flexible airplanes at high speeds, these elastic effects can probably be adequately accounted for by modification of the stability derivatives for elasticity.

REFERENCES

1. R. T. Jones, Unsteady Lift of a Wing of Finite Aspect Ratio, Report NACA TR 681, 1940.
2. Phillip Donely, Summary of Information Relating to Gust Loads on Airplanes, Report NACA TN 1976, November 1949.
3. R. T. Jones, Operational Treatment of the Non-Uniform Lift Theory in Dynamics, Report NACA TN 667, 1938.
4. R. L. Bisplinghoff, G. Isakson, T. H. H. Pian, H. I. Flomenhoft, and T. F. O'Brien, Report on an Investigation of Stresses in Aircraft Structures under Dynamic Loading, Massachusetts Institute of Technology, Jan. 21, 1949.

[redacted]

Chapter 4

Aircraft Experimental Program at Greenhouse

Program 8 at Greenhouse was designed to furnish experimental checks on the theories developed by MIT. The main concern was to obtain structural data, such as accelerations and bending moments, and also to compare qualitatively the overpressure damage with that which was incurred in the Aberdeen tests. To this end, the test aircraft were instrumented with accelerometers and strain gauges under the direction of personnel at Wright Air Development Center (WADC). Pressure gauges were placed at various stations in order to obtain information on chordwise pressure distribution as well as reflection effects. Information from the instruments was to be telemetered back as well as locally recorded on Webster magnetic-tape recorders.

Having decided on the desirable instrumentation, it was necessary to select locations for the aircraft. The factors considered in locating the aircraft were local damage caused by overpressure, damage to the main structure caused by material velocity, and also thermal radiation, nuclear radiation, and stability of the aircraft. Since no adequate previous experimental results existed, these factors could be evaluated only by referring to the theories which were to be checked at Greenhouse. The positions were chosen largely by determining wing-root bending moments at various positions by the methods presented in Chap. 3 and by comparing these bending moments with the design moments for the aircraft in question. Using positions thus determined as a base, the other factors were considered and were found, in general, to be less critical than the original gust criterion for the test aircraft.

For Dog Shot it was desired to subject the aircraft to loads smaller than the design loads in order to ensure their returning from the mission. The manned aircraft, of course, were placed in safe positions owing to crew-safety limitations. The philosophy behind the positioning was to obtain a feeling for the problem in Dog Shot and to verify the fact that the existing theories were not grossly in error. This information would make it possible to position the aircraft in succeeding shots at more critical positions with greater assurance that the predictions would be accurately fulfilled. Therefore for Dog Shot all drones were subjected to predicted loads smaller than the limit loads, and the manned aircraft were placed at positions such that they would receive less than half a gravity incremental acceleration.

The orientations of the aircraft were chosen in such a manner that information of a diversified type would be obtained. In a normal bomb run the bombing airplane would probably be going away from the point of burst when the shock wave caught it; therefore several of the airplanes were positioned in this manner. Some aircraft were located so that they were flying directly toward the point of burst. This orientation afforded a check on the generality of the theories as well as information on the relative pitching produced on aircraft flying toward and away from the point of burst. One airplane was placed off to the side to obtain, as before, a check on the generality of the theories and also information on the lateral motions of an aircraft exposed to an atomic burst.

The results of Dog Shot brought the thermal-radiation problem to the fore. The B-17 (slant range at T_0 16,000 ft) in that shot returned with the bottom surface of its fabric control surfaces burned off. As a result, it was obvious that, in order to carry out the original intent of

[redacted]

subjecting the aircraft to larger loads in Easy Shot, the underside of the fabric control surfaces must be protected. This was accomplished by covering them with a metal foil which helped protect the fabric by its greater reflectivity and by absorbing some of the heat. As far as structural damage was concerned, the results of Dog Shot seemed to indicate that the theories were substantially correct. Accordingly, a B-17 and a T-33 were located at positions which resulted in predicted loads equal to the ultimate loads. Special consideration was given to thermal radiation, particularly on the B-17's. Another consideration involved the method of recording the data. Since loss of an airplane through structural failure would be a total loss unless telemetering operated satisfactorily, an alternative set of locations subjecting the aircraft to lower loads was agreed upon for use if it appeared that telemetering would not function. The manned aircraft were again placed at low load positions, and particular attention was given to the thermal-radiation problem for the B-50's, which had fabric control surfaces.

The complete description of the instrumentation on all aircraft, as well as the specific drone- and manned-aircraft locations for each shot, may be found in the report on Project 8.1. Also included in that report are the data obtained from the instrumentation on the various aircraft. Correlation of these data with the theories developed at MIT will be presented in the formal USAF–MIT reports mentioned in Chap. 1.

Chapter 5

Recommendations

At the time of writing, the recommendations given are based on qualitative assessments of the Air Force participation in the 1951 Eniwetok tests. Formal conclusions and recommendations will be contained in the USAF–MIT series of reports on the entire problem. There are, however, some general recommendations which can be made at this time.

It is recommended that

1. The basic theoretical research be carried on continually on all important problems pertaining to the effects of blast on aircraft structures. One objective of this research should be directed toward specifying needed future test programs.
2. Technical and operational planning in order to accomplish the considered Air Force technical objectives should be formulated well ahead of the time of the test. The technical planning for the test should be so devised that a maximum of information is realized on the priority problems at hand.
3. Instrumentation for Air Force participation in atomic-weapon testing should be continually developed and proof-tested under operational conditions.
4. The instrumented aircraft used during the 1951 Eniwetok tests should be retained by WADC for utilization in future Air Force testing programs.

[redacted]

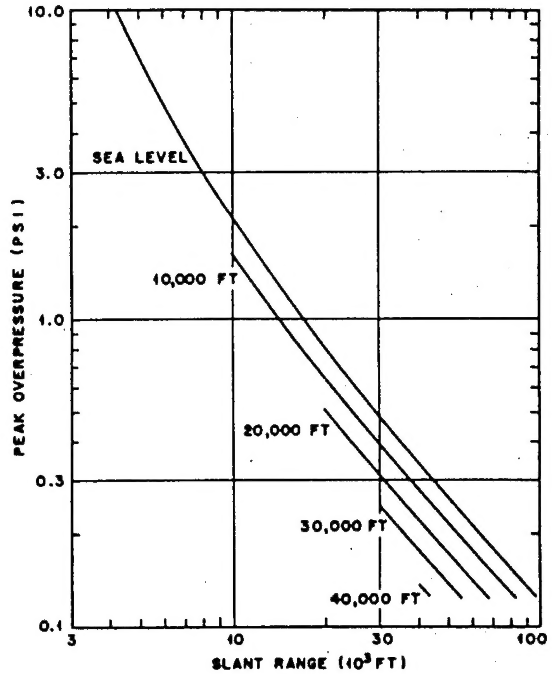

Fig. 2.1

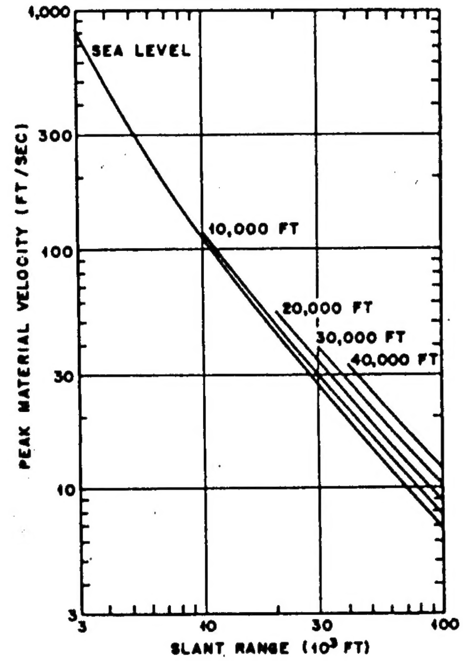

Fig. 2.2

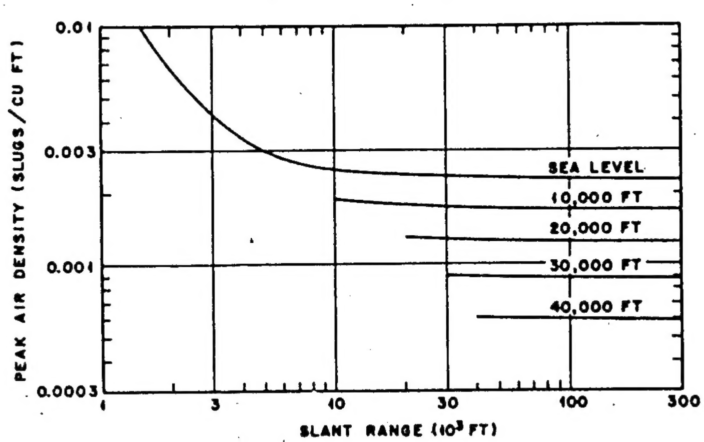

Fig. 2.3

Fig. 2.1 Peak Overpressure vs Slant Range for a 50-kt Bomb at Sea Level

Fig. 2.2 Peak Material Velocity vs Slant Range for a 50-kt Bomb at Sea Level

Fig. 2.3 Peak Air Density vs Slant Range for a 50-kt Bomb at Sea Level

[redacted]

[redacted]

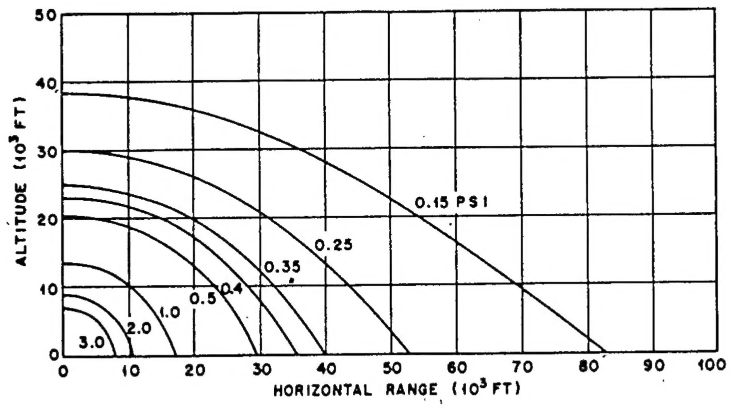

Fig. 2.4

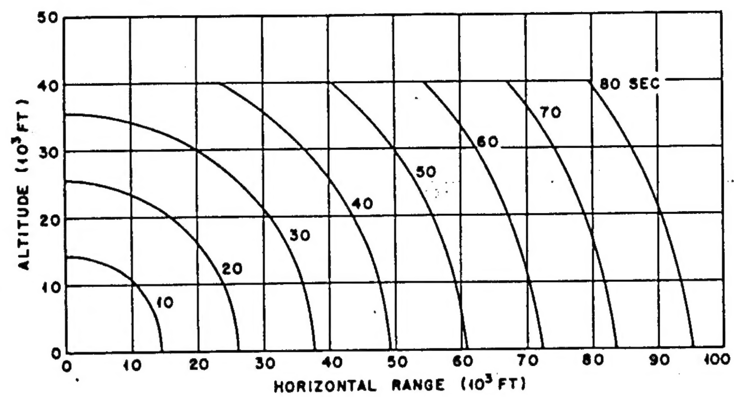

Fig. 2.5

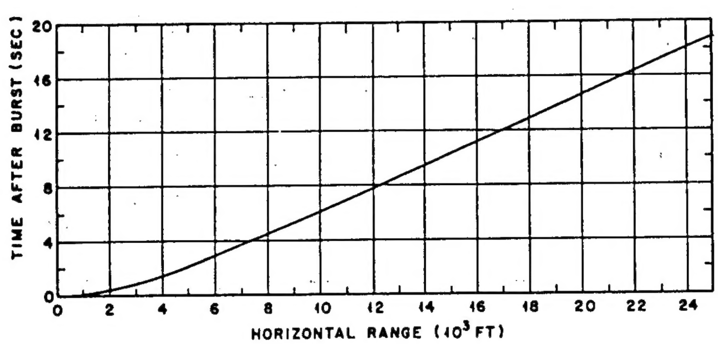

Fig. 2.6

Fig. 2.4 Isobars of Peak Overpressure for a 50-kt Bomb at Sea Level

Fig. 2.5 Positions of Shock Front in Space at Various Times after Detonation of a 50-kt Bomb at Sea Level

Fig. 2.6 Ground Intercept of Shock Front vs Time after Detonation of a 50-kt Bomb at Sea Level

[redacted]

[redacted]

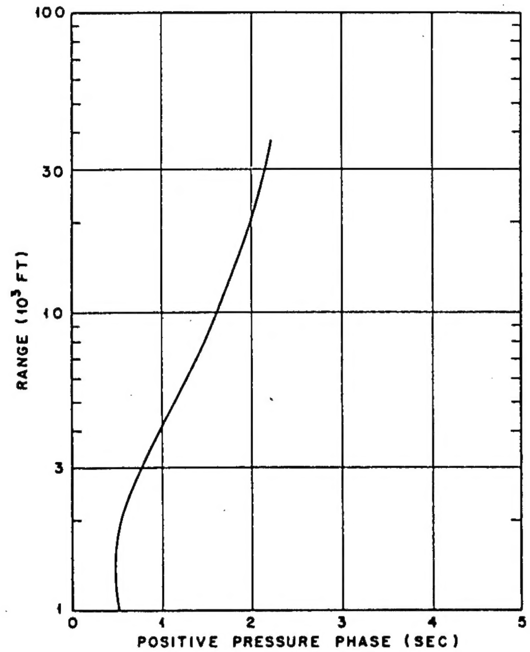

Fig. 2.7

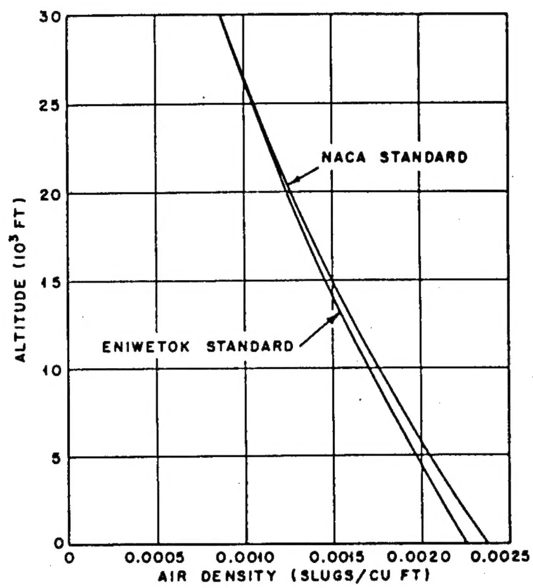

Fig. 2.8

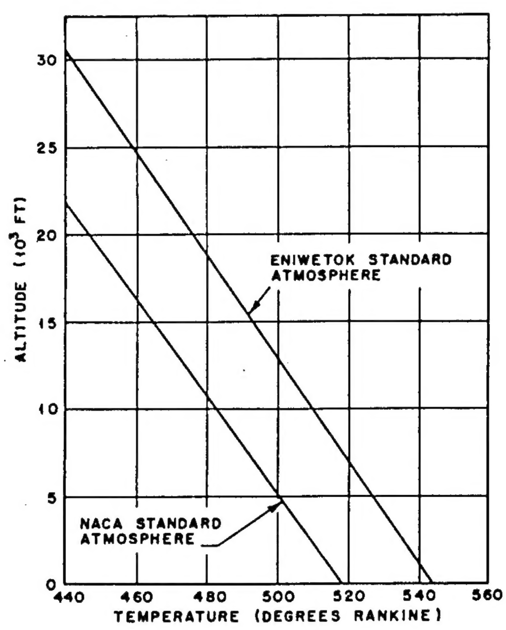

Fig. 2.9

Fig. 2.7 Duration at Sea Level of the Positive Pressure Phase of the Blast Wave for a 50-kt Bomb at Sea Level

Fig. 2.8 Comparison of Air Density in the NACA Standard and the Eniwetok Standard Atmospheres

Fig. 2.9 Comparison of Air Temperature in the NACA Standard and the Eniwetok Standard Atmospheres

[redacted]

 [redacted]

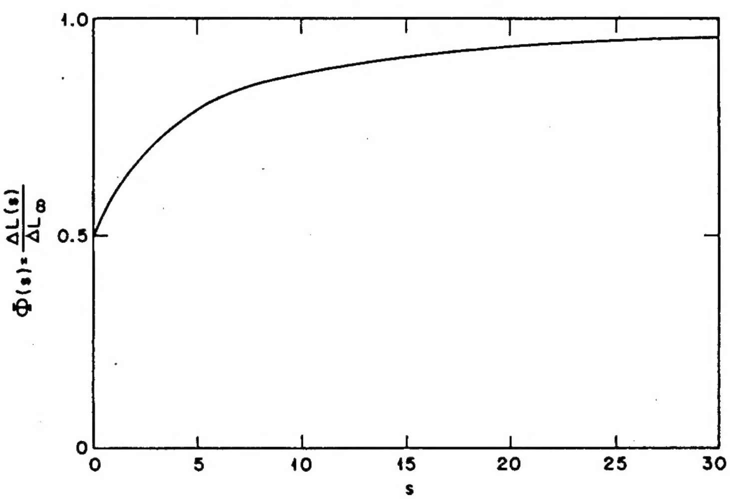

Fig. 3.1 The Wagner Function

[redacted]